A STUDY ON PERFORMANCES OF VARIABLE GEOMETRY TURBOFAN ENGINES UTILIZING AN APPROXIMATED ANALYTICAL METHOD

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Abstrat

A study of the influence on performances, specially on fuel consumption, of the effect of varying exhaust nozzles areas and specific work of the fan in two-spools turbofan engines is carried out.

The study is conducted by means of an approximated method, essentially based on substituting the performances maps of compressors, fan and turbines by means of approximated analytical expressions.

The approximation given by the method is verified by comparing results with those theor£ tically obtained without simplifications and with actual data obtained from air data computer measurements carried out in flight resulting in both cases excellent approximations.

Final results show that modest but significant reduction in fuel consumption may be obtained by varying the exhaust areas and specific work of the fan, which couples with important reductions in turbine inlet temperature. All this might be of special interest for large turbofan engines specially designed for short range aircraft.

Nomenclature

A	area
A_c, A_f	core and fan exhaust nozzle areas
A_{c*}, A_{f*}	design values of areas
K_1, K_2	constants
$\dot{m}$	mass flow rate
$\dot{m}_c$, $\dot{m}_f$	core and fan mass flow rates
$\dot{m}_{c*}$, $\dot{m}_{f*}$	design value mass flow rates
n	number of stages
N1, N2	rotational speeds
P	pressure
T	temperature
$\bar{r}_j$	average radius at stage j
SFC	specific fuel consumption
$\bar{V}_{zj}$	average axial air velocity at stage j
$\bar{\beta}_{rj}$	average angle of relative exit velocity at rotor of stage j
$\bar{\beta}_{s(j-1)}$	average angle of relative exit velocity at stator j-1
Λ	by-pass ratio
ω	angular speed
ρ	density
τ	specific work of compressors or fan

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Subscript

c	core flow
f	fan flow
i,e	inlet, exit conditions
t	total or stagnation conditions
*	design value

I.- Introduction

The utilization of variable geometry components in turbofan engines has been considered as an attractive possibility in order to reduce specific fuel consumption.

The introduction of these variable geometr; components has been hindered by three specific problems: higher costs of engines, increase of weight and added complexity, specially in connection with control systems.

High cost of fuels and the introduction of digital control systems have considerably offset these problems, and as a consequence, variable geometry engines are at the present moment a very promising research field.

Variable geometry, when aimed at reducing fuel consumption, is specially attractive for turbofan engines. In these engines, specific fuel consumption is a sensitive function of both by-pass flow ratio and specific work of fan, and the optimum values of these variables are very sensitive functions of aircraft speed.

By-pass ratio and specific work of fan are normally optimized at cruise speed. Therefore for take-off and climb these variables are not optimized and, as a result, it is possible to reduce fuel consumption acting on them.

The by-pass ratio can be modified by varying one or both exhaust nozzle areas of core flow and fan flow. Specific work of the fan may be modified by changing the pitch of the blades, or by placing variable angle inlet guide vanes.

The present work is a contribution to the study of the influence of varying exhaust nozzle areas and specific work of the fan on performances of turbofan engines and specially on specific fuel consumption.

The study has been carried out by utilizing a simplified analytical method which has been developed to that purpose.

II.- Calculation Method

Performances calculations of turbofan engines is a very lenghty numerical process. For a fixed geometry two spools turbofan engine it involves solution of a system of 34 equations relating 36 dimensionless variables: 20 equations of components, 12 matching equations and two equations expressing conditions, either critical or subcritical at the nozzles exhaust sections.

In addition of the two independent variables (usually the aircraft dimensionless speed and either a dimensionless rotor speed or the engine pressure ratio), each change in geometry adds a new independent variable.

The main difficulty for the solution of this system lies on the ten equations of compressors, fan and turbines, which are given in the form of performances maps. These maps have to be digitalized or approximated by means of polynomial expressions.

The approximated analytical method is essentially based on substituting these perfor_ mances maps by means of approximated analytical expressions, which are as follows:

a) Performances of both compressors and fan are given by expressions of the form (see Appendix):

$$\frac{\tau_k}{c_p\, T_{it}} = \frac{T_{et}}{T_{it}} - 1 = K_1 \left(\frac{Nj}{\sqrt{T_{it}}}\right)^2 - K_2 \left(\frac{Nj}{\sqrt{T_{it}}}\right)\left(\frac{\dot{m}_k \sqrt{T_{it}}}{P_{it}}\right) \qquad (1)$$

(i = inlet conditions; j = 1, 2; k = c , f)

where K and K_ are constants dependly only on the geometrical characteristics of each compressor or fan.

Efficiencies are obtained from the performances maps, as well as the values of K ar.d
V

b) It will be assumed that both turbines work at critical conditions, that is:

$$\frac{\dot{m}_t \sqrt{T_{it}}}{P_{it}} = \text{constant} \qquad (2)$$

Their efficiencies will be assumed to be constant and they will be obtained from the performances maps.

These assumptions apply in conditions varying from cruise to take-off, but not at medium and low rotational speeds, of regimes such as descent and taxying. However, these last regimes are not significant as far as fuel consumption is concerned.

The remainder equations of components, as well as all matching equations, are those normally utilized and they are of the analytical type. In this way, solution of the system is obtained through a relatively simple computer programme. Utilizations of the performances maps is avoided, except for surge limitations and efficiencies corrections.

The approximation given by the method has been verified, in the first place, by comparing the results given by the method with those obtained solving numerically the complete performances equations of a modern two spools large turbofan engine, for which all relevant data including performances maps were available.

Comparison of results for different exhaust areas at take-off and cruise conditions are given in Fig. 1. It may be verified that the approximation given by the method is excellent.

In the second place actual engine performance data obtained in a real flight, including take-off, climb and cruise conditions were compared with the same data calculated with the approximated method. Results of this comparison are showed in Table 1 and it may be seen that the approximation obtained i:: <jf the order of 1».

Actual engine performance data were recorded on a B-747 flight, with tha AIDS system (Aircraft Integrated Data System). Engine constants needed for the utilization of the approximated method were obtained from ground test cell where the engine was tested before installed in the aircraft.

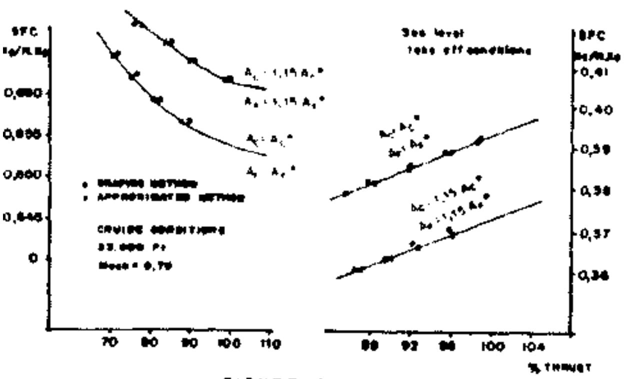

FIGURE 1

COMPARISON ACTUAL DATA VS CALCULATED DATA

FIGHT LEVEL (Ft)	MACH NUMBER	N1		N2	ENGINE PRESSURE RATIO	TURBINE TEMP. °K	FUEL FLOW Kg/h
302	0	3414	A	7500	1.450	879	7801
			C	7450	1.439	865	7740
11700	0.602	3415	A	7329	1.379	847	6897
			C	7350	1.392	839	6805
17000	0.665	3380	A	7267	1.368	827	5836
			C	7280	1.385	818	5802
22300	0.734	3425	A	7242	1.464	820	5389
			C	7260	1.478	811	5216
25000	0.777	3406	A	7197	1.476	810	4989
			C	7210	1.481	799	4925

A: Actual data. C: Calculated data.

TABLE 1

III.- Results

The study of the influence of the variation of exhaust areas A_c and Af on performances and on the specific fuel consumption may be carried out in different ways, depending on the engine parameter selected to control the process. In this analysis it has been selected to keep constant thrust when the exhaust areas are varied, because this variable geometry system would be specially applicable for take-off. Keeping constant thrust would be a simple matter for the fuel control system by means of engine pressure ratio indications.

Figs. 2 and 3 show the variations of the most important parameters for a typical large two spools turbofan engine as functions of areas A_c and Af when they are increased up to 25* of their design value AJ and Af at take-off.

Fan or LP compressor speed *H]* increases significantly, and HP compressor speed N_2 decreases; both core mass flow TOJ- and fan flow if augment and combustion or inlet HP turbine temperature decreases.

As might be expected in a large by-pass ratio engine, the influence of the variation of the fan exhaust area Af is more important than the influence of A_c.

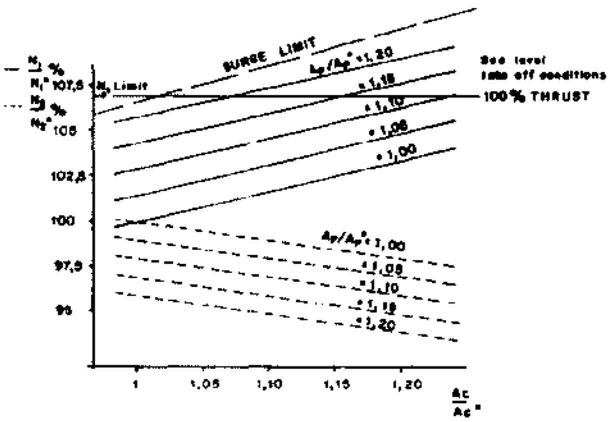

FIGURE 2

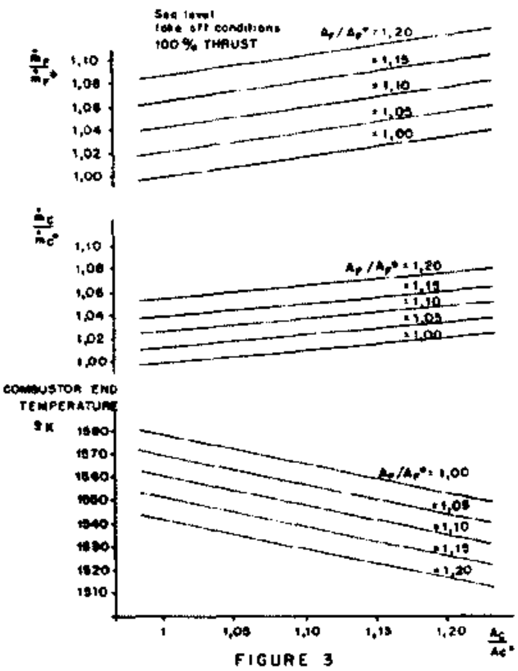

FIGURE 3

The above mentioned laws of variation impose limiting value to maximum increase of exhaust areas. In the first place, Ni cannot surpass its maximum design operational value, usually of the order of 5-8% higher than normal take-off speed. In addition, operational point at the LP compressor moves towards the surge line, when A_c or Af increase, imposing another limiting value to A_c and Af. On the other hand, HP compressor and fan operational points move away from the surge line, placing no restrictions. These operational restrictions limit the maximum values of A_c and Af. For the engine considered, these maximum values were of the order of 15* higher than their design values.

The significant reduction in inlet turbine temperature during take-off, which may be of the order of 50°C, is an important feature of the variable area system.

It is important to point out that all results and limiting values have been obtained for an engine designed for fixed exhaust areas. It is evident that in order to achieve full advantage of the variable geometry, an engine should be designed to that purpose.

Fig. 4 shows results obtained for the specific fuel consumption (SFC) at take-off and cruise conditions. As might be expected, at cruise conditions increase in exhaust areas leads to increase in SFC, showing that the design value of areas A£ and A| were optimized for these cruise conditions. On the other hand, at take-off reductions of SFC of the order of 6% may be obtained with exhaust areas increase of the order of 15%.

Values of A_c and Aj up to 25% higher than their design value were also included, which roughly represent maximum practical values if restrictions on values of H^ and on surge limits of LP compressor were removed. In this case, reductions of SFC at take-off the order of 7.5% might be achieved.

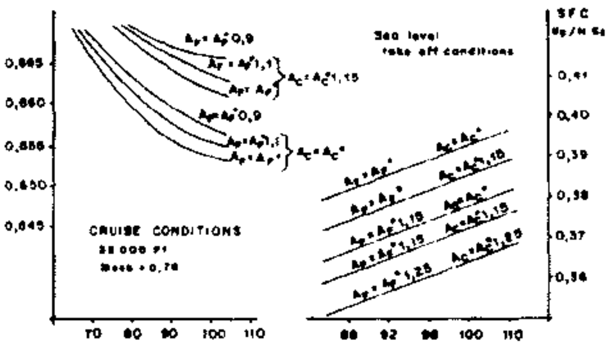

FIGURE 4

Figure 5 gives the reduction in total fuel consumption that could be obtained in a typical flight as function of flight time. The fuel consumption has been calculated optimizing the laws of variation of A_c and Aj during take-off and clinb.

It may be seen that significant reduction in fuel consumption may be obtained, specially in short flights and if full increase of exhaust areas is allowed.

The case of a single exhaust area has also been studied. Results obtained by changing the exhaust area are similar to those presented in this work. However it may be pointed out that if mixing losses of core flow and fan flow are small, slight reductions in specific fuel consumption may be obtained at cruise conditions with only one exhaust nozzle as compared with the values obtained with two separated flows.

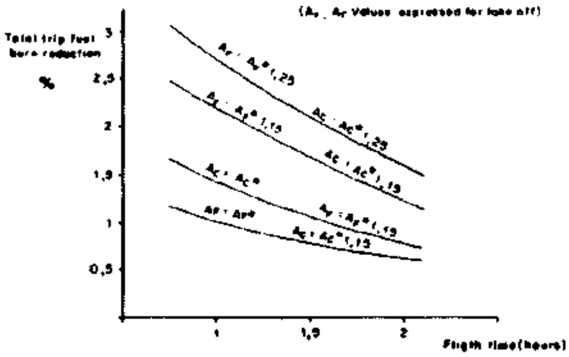

FIGURE 5

Finally, the influence ..; : .,• .... ^Uui, of the specific work of the fan has been studitt: as a first approximation at constant «•*' " • • y.

Results are shown in fig. 6, wi.*v,, <".- oeen obtained at constant Aj, and varying the by-pass ratio by changing A_c. It may be seen that reduction of SFC of the order of 5% at take-off conditions may be obtained by reducing the specific-work of the fan in a 20*. However this requires an increase in the area A_c of the order of 20* and a high increase of fan speed Nj well above its design value.

Variation of area:- .-.,, ..,.,. ,,,. ..»., natively simple modifications of the engine, specially if the turbofan has only one exhaust area, and if the mechanism could be coupled with the thrust reverse system. On the one hand, pitch change of the fan blades is a major modification, and on the other hand the introduction of inlet guide vanes may give rise to noise and possible vibrations problems in the fan.

It may be concluded that thi. ™,.t..,v, but significant reductions in fuel consumption that can be obtained by varying the exhaust nozzles of core and fan flows, coupled with the important reductions at take-off of the inlet turbine temperature, would appear to be a promising field for development, especially for large by-pass engines designed for short range aircrafts.

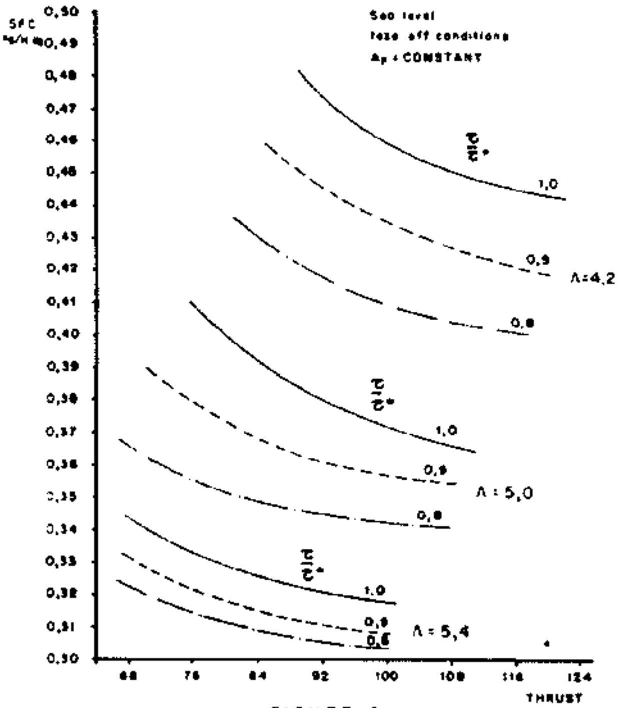

FIGURE 6

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Appendix

Derivation of the analytical expression of compressor performances.

The specific work of an axial compressor of n stages may be expressed as follows:

$$\tau = \sum_{j=1}^{n} \omega^2 \bar{r}_j^{\,2} - \sum_{j=1}^{n} \omega \bar{r}_j \left[\bar{V}_{zj} \tan \bar{\beta}_{rj} - \bar{V}_{z(j-1)} \tan \bar{\beta}_{s(j-1)} \right] \quad (3)$$

In this expression angles β_{rj} and β_{sj} of the relative exit velocities at rotor and stator blades may be taken as approximately constant, for all normal working conditions of the compressor.

Assuming that the average axial velocity $\bar{V}_{zj}$ is constant throughout the compressor, which is an assumption close to actual conditions in most compressors it results:

$$\tau = \omega^2 \sum_{j=1}^{n} \bar{r}_j^{\,2} - \omega \bar{V}_z \sum_{j=1}^{n} \bar{r}_j \left[\tan \bar{\beta}_{rj} - \tan \bar{\beta}_{s(j-1)} \right] \quad (4)$$

and with:

$$\bar{V}_z = \frac{\dot{m}_k}{A_{ik} \rho_i} \approx \frac{\dot{m}_k}{A_{ik} \rho_{it}} \qquad (k = c,\ f) \quad (5)$$

it may be obtained:

$$\tau = \omega^2 C_1 - \omega \dot{m}_k C_2 \frac{T_{it}}{P_{it}} \quad (6) \qquad (C_1, C_2 \text{ constants})$$

and then the expression (1) of the text is finally obtained:

$$\frac{\tau}{c_p T_{it}} = K_1 \left(\frac{N_j}{\sqrt{T_{it}}} \right)^2 - K_2 \left(\frac{N_j}{\sqrt{T_{it}}} \right) \left(\frac{\dot{m}_k \sqrt{T_{it}}}{P_{it}} \right)$$